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The Quest for Neutrino-less Double Beta Decay

Andrea Pocar*

Physics Department, University of Massachusetts, Amherst MA 01003

Abstract

We review the status and future of ongoing searches for neutrino-less double beta decay, a lepton-number violating nuclear decay whose existence would imply that neutrinos are their own antiparticles, *i.e* Majorana particles. The measurement of its decay rate is arguably the most sensitive laboratory probe of the absolute mass of neutrinos. Emphasis is given to the most promising detector technologies in the field which aim at exploring the inverted hierarchy region of neutrino masses.

Keywords: neutrino masses, lepton number violation, low background detectors

1. The physics of neutrino-less double beta decay

Shortly after the introduction of the neutrino in the family of elementary particles by Pauli and the first theory of beta decay by Fermi, Maria Göppert-Meyer, following a suggestion by Bethe, proposed the existence of an exceedingly rare second order nuclear process with the simultaneous emission of two electrons for nuclei for which the single beta decay was energetically forbidden. Her calculations pointed to half lives for such process in excess of 10^{17} years [1]. *Two-neutrino* double beta decay ($2\nu\beta\beta$), the standard weak process with two emitted electrons accompanied by two electron-flavored antineutrinos, has now been observed for ∼10 even-even nuclei with half lives in the range of $\sim 10^{19}$-10^{21} years, first geochemically of ^{130}Te, then of ^{82}Se in a laboratory experiment [2].

While the observation of $2\nu\beta\beta$ is a remarkable technical achievement in its own right, the motivational drive to design, build and operate detectors capable of measuring such rare signals was and still is the quest for a non-standard reaction, *neutrino-less* double beta decay ($0\nu\beta\beta$). A nuclear process where the two electrons (and no neutrinos) are emitted in the final state, $0\nu\beta\beta$ violates the empirically-motivated Standard Model symmetry of lepton number conservation. Allowed, if not predicted, by supersymmetric extensions to the Standard Model, and able, if observed, to point to a leptonic origin of the baryon asymmetry in

*Email: pocar@physics.umass.edu; URL: http://people.umass.edu/pocar

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the universe via a mechanism known as leptogenesis [3], $0\nu\beta\beta$ would also imply that neutrinos and anti-neutrinos are the same particle, *i.e.* Majorana particles.

While there might exist different mechanism for $0\nu\beta\beta$ which draw from more or less exotic extensions of the Standard Model, the simplest and arguably the most appealing is that of a virtual exchange of a massive Majorana neutrino (see fig. 1). The half life of such a process is related to an effective neutrino mass term, specifically to a coherent superposition of the three known light neutrinos:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z) \cdot |M^{0\nu}|^2 \cdot < m_{\beta\beta} >^2 \tag{1}$$

where G is a phase space factor and M is the nuclear matrix element between initial and final state [4][1]. Substantial progress has been made in the last decade in calculating $|M^{0\nu}|$ using several different approximations and models which now show a converging trend for their calculatd values. Nuclear matrix elements for the isotopes being used in most experimental searches, is between 1 and 6 [2]. According to the equation above larger NME's quadratically correspond to faster decay rates and are hence related to favorable isotopes. However, other factors such as the end point energy, ease of isotopic enrichment, chemical and physical properties and detector layout all weigh into the choice of the isotope for an experiment. In turn, the mass term is:

$$< m_{\beta\beta} >^2 = |\sum_{i=1}^{3} |U_{ei}|^2 e^{i\alpha_i} m_i|^2 \tag{2}$$

where m_i are the masses of the three light neutrinos, U_{ei} the electron-elements of the unitary neutrino mixing matrix and α_i are the Majorana phases allowed by the symmetries of Standard Model lagrangian. It should be noted how because of the coherent nature of the neutrino superposition, there might exist combinations of the α_i phases for which $< m_{\beta\beta} >$ vanishes even if all neutrinos are massive Majorana particles. Fig. 2 illustrates the neutrino mass sensitivity for current and planned experiments compared with neutrino mass ranges allowed by neutrino oscillation experiments. In case the neutrino mass hierarchy is inverted (*i.e.* the neutrino which has mostly electronic flavor is the heaviest of the three) the effective neutrino mass measured via double beta decay is larger than 10 meV, a natural target sensitivity target for future experiments.

For completeness, it should be noted that the emission of two electrons is not the only way to double beta decay. In fact double electron capture and double positron emission are also possible for proton-rich nuclei. Also, the double beta decay process could occur to excited states of the daughter nucleus with successive emission of γ quanta. These processes will not be discussed in this review (the reader can refer to [2]).

2. Detection strategies and different experimental approaches

In the standard $2\nu\beta\beta$ process, the two electrons carry away only a fraction of the available energy, Q, of the decay. The kinetic energy is shared with the two neutrinos and the sum energy spectrum of the two electrons is continuous and similar to what is observed in single beta decay. In $0\nu\beta\beta$ decay, the to electrons share the entire available kinetic energy (neglecting the tiny amount that makes the daughter nucleus recoil) and the sum of their energy is hence Q. A peak-like feature in the sum energy spectrum of the emitted electrons is what experiments look for to distinguish the two double beta decay modes. Because of finite energy resolution effects, a small but significant fraction of $2\nu\beta\beta$ events is reconstructed at and around the decay endpoint and is a background to $0\nu\beta\beta$ decay searches. Sharp energy resolution is thus an important feature of $0\nu\beta\beta$ decay detectors (see figure 3). Half lives for $2\nu\beta\beta$ for different isotopes are listed in table 1.

Because the sought-after signal is extremely faint, it is important that all efforts are made to minimize backgrounds. Double beta decay experiments are run deep underground where muons (and in turn their cosmogenically produced backgrounds) are highly suppressed. Typically, the detectors are made with the

[1]the equivalent expression for the $2\nu\beta\beta$ process is $(T^{2\nu}_{1/2})^{-1} = G^{2\nu}(Q,Z) \cdot |M^{2\nu}|^2$, where the nuclear matrix element (NME) has dimensions of inverse energy.

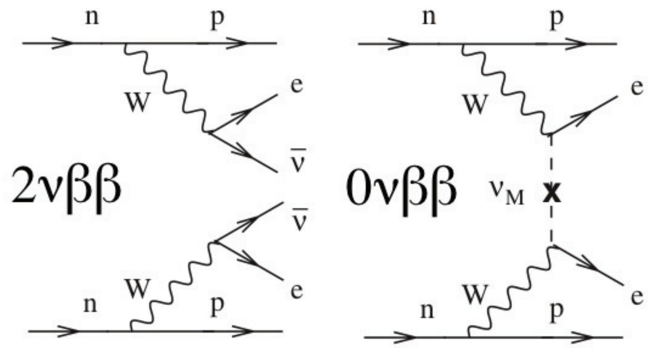

Fig. 1. The two double beta decay processes: the standard one with the emission of two neutrinos ($2\nu\beta\beta$, left) and the non-standard one in which just two electrons emerge in the final state ($0\nu\beta\beta$, right). If interpreted as the virtual exchange of a massive, light Majorana neutrino $0\nu\beta\beta$ allows to measure the absolute neutrino mass via eq. 1.

radiologically quietest materials possible, selected with lengthy and tedious material screening and their construction is carried out in clean rooms. Tough measures are usually taken to eliminate environmental radon and the plate out of its daughters for parts exposed to air. Other properties that can make double beta decay experiments successful are the ability to discriminate different classes of ionizing events (α, β and γ, etc), the possibility of handily purify the source isotope, and the ease of concentrating the isotope under study via isotopic enrichment (most double beta decay emitters are present at the 5-10% level or less in nature, with the exception of ^{130}Te at ~30%.).

In the following subsections we review some of the most competitive approaches to double beta decay searches with large detectors. The list is inevitably incomplete and reflects the view of the field held by the author. Experiments are divided by source and utilized technology in order to highlight advantages and disadvantages of the various approaches. A complete bibliographic reference for all existing experiments is beyond the scope of this report and we refer to reader to reference [2].

2.1. ^{76}Ge experiments

Experiments using ultra-pure ^{76}Ge detectors take advantage of a proven technology displaying superb energy resolution (~0.15% FWHM). In fact, a somewhat disputed claim for the observation of $0\nu\beta\beta$ in ^{76}Ge (with $T_{1/2} \sim 2 \cdot 10^{25}$ years, corresponding to $< m_{\beta\beta} >\sim 300$ meV) has been made by Klapdor-Kleingrothaus et al. [17] which awaits being tested with both ^{76}Ge and other isotopes. This experiment, which used ~10 kg of 90%-enriched germanium crystals and is decommissioned since 2003, still holds the best sensitivity

isotope	Q [keV]	$T_{1/2}^{2\nu\beta\beta}$ [10^{19} y]	$M^{2\nu}$ [MeV^{-1}]	reference
^{48}Ca	4271	$4.3^{+2.4}_{-1.1} \pm 1.4$	0.05 ± 0.002	[7]
^{76}Ge	2039	$(1.74 \pm 0.01^{+0.18}_{-0.16}) \times 10^2$	0.05 ± 0.002	[8]
^{82}Se	2995	$9.6 \pm 0.3 \pm 1.0$	0.10 ± 0.01	[9]
^{96}Zr	3350	$2.35 \pm 0.14 \pm 0.16$	0.12 ± 0.01	[10]
^{100}Mo	3034	$(7.11 \pm 0.02 \pm 0.54) \times 10^{-1}$	0.23 ± 0.01	[9]
^{116}Cd	2802	$2.9^{+0.4}_{-0.3}$	0.13 ± 0.01	[11]
^{128}Te*	868	$(1.9 \pm 0.1 \pm 0.3) \times 10^5$	0.05 ± 0.005	[12]
^{130}Te	2529	$(7.0 \pm 0.9 \pm 1.1) \times 10$	0.033 ± 0.003	[13]
^{136}Xe	2458	$(2.11 \pm 0.04 \pm 0.21) \times 10^2$	0.019 ± 0.001	[15]
^{150}Nd	3367	$(9.11^{0.25}_{-0.22} \pm 0.63) \times 10^{-1}$	0.06 ± 0.003	[16]

Table 1. A compilation of measured $2\nu\beta\beta$ half lives and nuclear matrix elements. *from geochemical ^{128}Te/^{130}Te ratio (thanks to Petr Vogel).

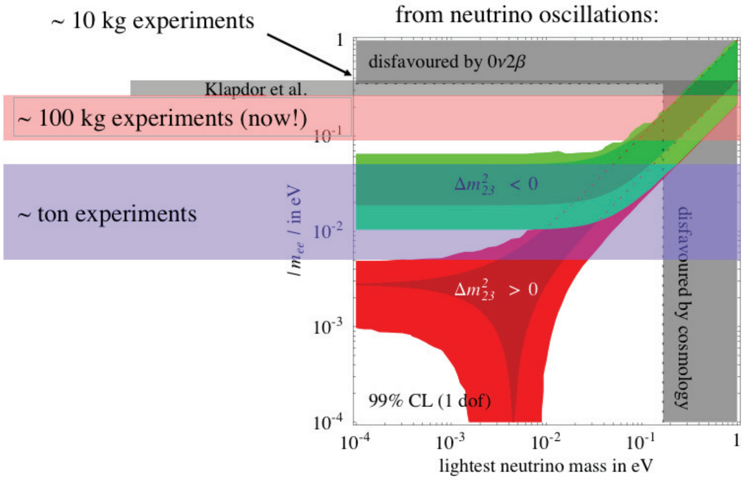

Fig. 2. Mass sensitivity of current and future generation double beta decay experiments. Experiments, like EXO-200 employing ~100 kg sources reach sensitivities of ~100 meV for $< m_{\beta\beta} >^2$. Many collaborations aim at exploring the inverted neutrino mass hierarchy defined by neutrino oscillation parameters with ton-scale experiments (see text for details). It should be noted that the "100 kg" and "ton-scale" classification is for illustrative purposes only and that each experiment has different mass sensitivity per unit source mass, depending on the isotope and technical design choices. The figure is adapted from [5].

for double beta decay experiments. There are currently two efforts: GERDA at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, and Majorana in the US. Both have the ultimate objective of a tonne-scale experiment, for which they are following a phased approach and plan to eventually merge efforts.

2.1.1. *Majorana*

The Majorana collaboration is working on a first-phase detector, the Majorana demonstrator to be housed at the 4850-foot level of the Homestake mine in South Dakota with the goal of proving backgrounds low enough to justify a tonne-scale experiment. Its science goal is to test the claim of observation of $0\nu\beta\beta$ in the same isotope. It is a compact detector, with passive Cu/Pb shielding employing a planned 40 kg of Ge crystals, with up to 30 kg of them enriched in the ^{76}Ge isotope (20 kg already in hand). Particular care is taken to control cosmogenic activation of the Ge crystals and the surrounding Cu. The Majorana collaboration has pioneered the in-house, underground production of electro-formed copper structures to be used in the innermost parts of the experiment. The schedule for Majorana foresees the deployment of 2-3 strings (a set of stacked detectors) of three natural (*i.e.* not enriched) crystals by late 2012 followed by the addition of enriched detector strings. By the second half of 2014 the detector should run with 14 strings of enriched Ge detectors in two cryostats, able to reach a background event rate of 4 counts/(t-year) in a 4 keV window around the 2039 keV end point of ^{76}Ge. One very promising tool is the use of point-contact detectors that have the particular ability, not shared by other Ge detector designs, to efficiently discriminate multi-site energy deposition within individual crystals by defining an electric field pattern which assigns unique drift times to ionization electrons produced in different positions inside the detector [19]. The sensitivity for a one tonne Ge experiment with background at or better than the Majorana demonstrator goals quoted above would allow to reach an effective neutrino mass sensitivity of 40 meV in one year of running, enough to start exploring the inverted mass scale (see fig 4).

2.1.2. *GERDA*

The GERDA experiment at LNGS also has a phased approach towards testing the positive claim of observation of $0\nu\beta\beta$ decay in ^{76}Ge. The basic design on how to best run the enriched Ge crystals differs substantially from the Majorana approach. GERDA, which started the commissioning run in June 2010 with natural Ge detectors, immerses strings of bare crystals in a large liquid argon (LAr) bath (fig. 5). The

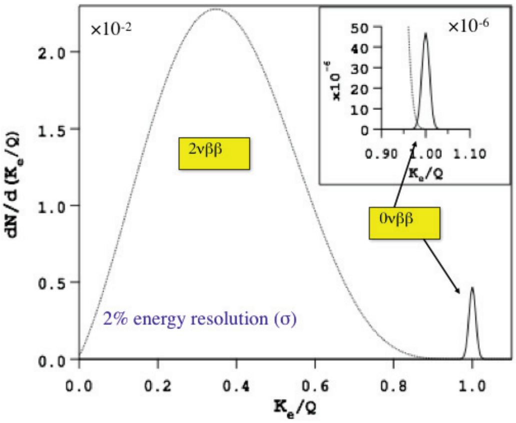

Fig. 3. Conceptual energy spectrum for the search of neutrino-less double beta decay. When the energy of the two emerging electrons is measured, the $2\nu\beta\beta$ process shows a characteristic continuous energy spectrum. The $0\nu\beta\beta$ is identifiable by the characteristic peak at the decay endpoint energy, which is the main feature experiments try to identify. The figure uses a 2% energy resolution (FWHM) for illustrative purpose, as each experiment will differ [6].

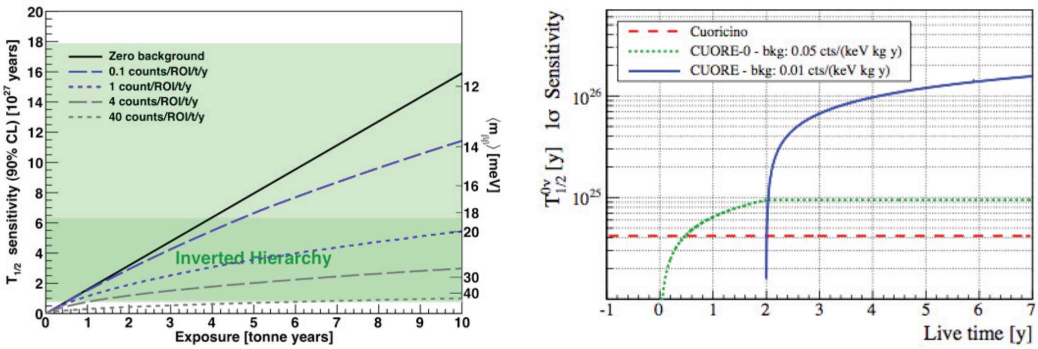

Fig. 4. The projected effective Majorana neutrino mass sensitivity for a tonne-scale germanium experiment for different background scenarios (left, nuclear matrix elements from [18], with g_A=1.25) and the CUORE bolometric experiment (from [22]).

argon cryostat is in turn contained inside a large water tank instrumented as a Čerenkov muon veto detector. This design provides excellent shielding from external background (γs and neutrons) and reduces possible muon-generated backgrounds such as untagged spallation neutrons (*e.g.* from Pb) close to the source. The initial engineering run has identified an unexpectedly large background, *i.e.* that from ^{42}Ar, present in trace amounts in natural argon. The problematic events for GERDA are those of ^{42}K which include an energetic de-excitation γ ray. The mechanism is that ^{42}Ar decays, then the potassium ion drifts toward the biased Ge crystals and deposits on their surface. The rate of ^{42}K decays observed by GERDA implies an abundance of ^{42}Ar in natural argon $\sim$10 times larger than previously measured [20]. Measures adopted to suppress this background have already proven at least partially successful. A further rejection tool for this and other backgrounds will be provided by instrumenting the LAr with PMTs which will allow surface decays on the crystals to be identified and quantified. A first physics phase for GERDA will see the deployment of eight enriched Ge crystals from the now decommissioned IGEX and Heidelberg-Moscow experiments ($\sim$ 18 kg), along with six natural Ge detectors, with the goal to prove a background of 10^{-2} counts/kg/y/keV at the endpoint. Following, a second phase with new enriched Ge detectors will aim at improving the background by another factor of ten.

Fig. 5. Left: GERDA experiment in Hall A at LNGS (visible is water tank + clean room). Right: a sketch of the CUORE cryostat.

2.2. *Bolometric experiments*

Bolometric techniques are well suited for the search of rare, low energy events. They display excellent energy resolution, and measure energy by the slight change in temperature, enhanced by the T^3 behavior of the heat capacity at very low temperature (small fraction of 1K). Many crystals can be run as bolometers, including some with double beta decaying isotopes.

2.2.1. *CUORE*

The Cuore collaboration uses arrays of tellurium oxide (TeO_2) crystals. ^{130}Te is the only naturally relatively abundant double beta decaying isotope, existing in nature with 34% abundance in natural Te, which does not require isotopic enrichment and hence simplifies the experimental effort. A first phase experiment, Cuoricino, was run at LNGS in 2003 and has set a lower limit to the half life of ^{130}Te of $2.8{\cdot}10^{24}$ years, with a ~20 kg-year exposure [21]. This translates to an upper limit of the effective neutrino mass of 300-710 meV, depending on the choice of nuclear element model adopted. This limit does not explore the entire mass range claimed by Klapdor et al. A large CUORE experiment is currently under construction at LNGS with 988 bolometers and ~200 kg of ^{130}Te and is scheduled to start operating in 2012 with a small fraction of detectors in the Cuoricino cryostat (CUORE-0 phase), and in 2014 with the entire detector (fig. 5). The CUORE design takes advantage of the close packing of the crystals for rejection of multiple hit events and also showcases improvements from Cuoricino, especially in the backgrounds from the Cu supports of the crystals and understanding of surface contamination. The design sensitivity is $T_{1/2} \sim 10^{26}$ for a neutrino mass sensitivity of 47-87 meV if the goal background of 0.01 events/kg/y/keV or better is met (see fig. 4).

2.2.2. *Scintillating bolometers*

A promising improvement of the bolometric technique comes from surface sensitive and scintillating bolometers, still at an R&D phase. Examples containing double beta emitters are $CdWO_4$ and $ZnMoO_4$, both particularly suited to discriminate surface α events [23], one of the main identified sources of background for Cuoricino, which produce a continuum background tail into the $0\nu\beta\beta$ energy region when heat alone is measured ($ZnMoO_4$ also has discrimination power via pulse shape analysis of the heat signal). The Lucifer program [24] is designing ZnSe scintillating bolometers with 10 kg of ^{82}Se to be run in the Cuoricino cryostat after CUORE-0 is completed with the goal of reaching a background of 0.006 counts/keV/y/kg or better.

2.3. *Tracking detectors*

An extremely successful technology for the detection and detailed study of the standard $2\nu\beta\beta$ process has been pioneered by the NEMO3 experiment. By using large area, thin double beta emitting foils and placing them inside a gas tracker ending in a calorimeter on both sides, very clean electron tracks can be reconstructed and the half life for $2\nu\beta\beta$ of many isotopes was measured (some found in table 1, see fig. 7 for an example). The presence of a magnetic field allows charge discrimination to separate double beta events from pair producing interactions. The limitations of such technology are these foils and relatively poor energy resolution, needed for high sensitivity $0\nu\beta\beta$ searches. The NEMO collaboration believes they can make a worthwhile 100 kg scale experiment, SuperNEMO, using ^{82}Se with a 4% energy resolution at the 3 MeV endpoint and able to reach a half life sensitivity of $2{\cdot}10^{26}$ year sentivity (50 meV neutrino mass sensitivity). A somewhat similar technology with foils and scintillator is used by the MOON collaboration which is planning on using ^{100}Mo as source.

2.4. *Liquid scintillator-based experiments*

A completely different approach to double beta decay detection is that to dissolve the source in a large liquid scintillator detector (adapted or built specifically for the purpose). Many hundreds of kilograms of isotope can be dissolved with some non-trivial chemistry in the case of heavy metals in large, kiloton-scale experiments such as KamLAND or Borexino. The idea for such experiments came many years ago from Raghavan and was re-proposed by members of Borexino [25]. There are currently two experiments following this path, SNO+ and KamLAND-Zen. These experiments with their abundant source inventory will have high signal statistics and superb intrinsic purity (from the experience with Borexino and KamLAND) and shielding from external γ radiation. Because of relatively poor energy resolution of liquid scintillator detectors, rather than a $0\nu\beta\beta$ peak at the endpoint, these experiments look for a statistically well-defined shoulder with an excess of events at the high energy end of the $2\nu\beta\beta$ spectrum.

2.4.1. *SNO+*

The SNO+ collaboration plans to dissolve one ton of natural neodimium (Nd) in refurbished SNO detector at SNOLab in Sudbury, Canada, with 1 kton of liquid scintillator (0.1% concentration). The low concentration preserves good optical properties of the scintillator, necessary for position and energy resolution, and ^{150}Nd (5.6% natural isotopic abundance for 44s kg of double beta decaying source in SNO+) holds the promise of a particularly advantageous nuclear matrix element as well as a Q-value (3.3 MeV) well above most natural radioactivity backgrounds. A 100 meV neutrino mass sensitivity is foreseen with a 2013 start date.

2.4.2. *KamLAND-Zen*

The KamLAND detector at the Kamioka mine in Japan is being refurbished and a thin (25 μm) containment balloon installed that will contain 400 kg of xenon (90% enriched in ^{136}Xe dissolved at 3% concentration in 10-15 tonnes of liquid scintillator, see fig.řeff:xe). The advantage of containing the double beta isotope in the center of the detector rather than in the entire scintillator volume is that of providing better shielding from external γ rays and the reduction of systematic effects related to non-uniform spatial response of the detector. The aggressive design goal for KL-Zen is to reach a 60 meV neutrino mass sensitivity in 2 years, and $\sim$30 meV in five years with 1 tonne of xenon, probing the inverted mass hierarchy [26]. The level of intrinsic scintillator backgrounds following purification and inner balloon installation as well as the energy resolution at the end-point will be crucial in defining the ultimate sensitivity of this technique.

2.5. *Pure ^{136}Xe experiments*

The gaseous nature (at room temperature and standard pressure) of ^{136}Xe gives it a special place in the list of candidate double beta decay isotopes. Its isotopic enrichment is by now well-proven and simpler than for other elements, as it does not involve complicated chemistry. Whether it is used in gas or liquid form, xenon detector technology has already proven to allow for very low background experiments which take advantage of the relative ease of purification of xenon, which can be repeated during the operation of

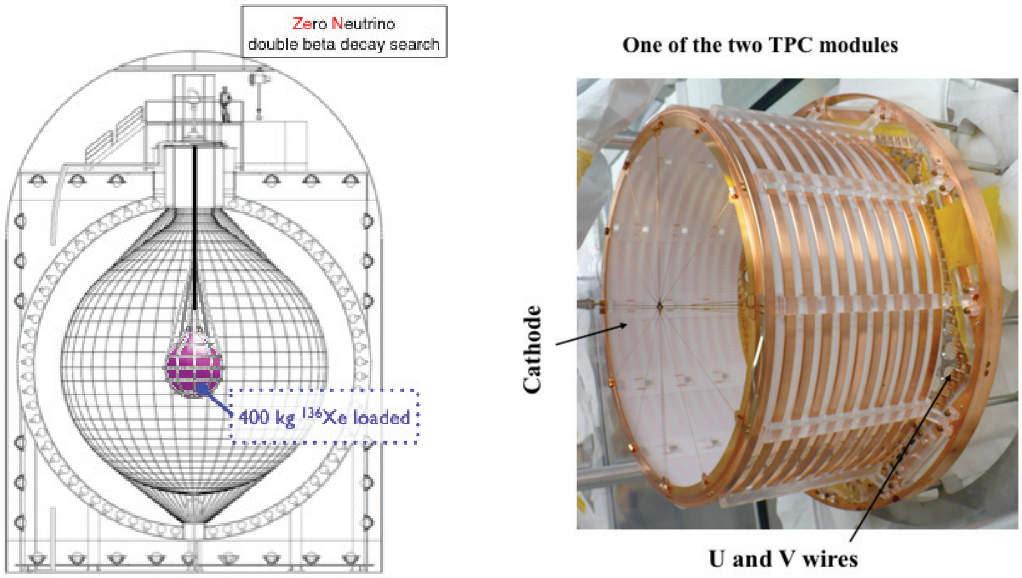

Fig. 6. A schematic view of the KamLAND-Zen experiment, with the central Xe-loaded scintillator contained in a thin transparent balloon (left) and a picture of one half of the inner TPC of the EXO-200 experiment (right). These two experiments both search for $0\nu\beta\beta$ decay of ^{136}Xe using enriched xenon, but employ vastly different approaches.

the experiments. While energy resolution for the ionization channel of gaseous xenon is very good, that of xenon liquid in either the ionization or scintillation channel alone is quite modest. It was shown [27] that with the simultaneous collection of ionization and scintillation the energy resolution of LXe at the ^{136}Xe endpoint energy of 2.5 MeV can be 1-1.5%, adequate for sensitive $0\nu\beta\beta$ decay searches.

2.5.1. NEXT

The NEXT collaboration is designing a 100 kg enriched, high pressure gaseous xenon experiment. In GXe, the tracks of two electrons from double beta decay can be identified and separated from events with one single electron of the same total energy, like those arising from Compton scattering of energetic γ rays, currently the main background for all neutrino-less double beta decay experiments. The NEXT collaboration could run as soon as 2013 at the Canfranc underground laboratory in the Pyrenees and reach a background level of $2{\cdot}10^{-4}$ events/kg/y/keV at the endpoint.

2.5.2. EXO

An older experiment looking for $0\nu\beta\beta$ decay of ^{136}Xe is EXO. Its first phase experiment uses 175 kg of 80% enriched liquid xenon (LXe) in a double time projection chamber (TPC) with scintillation readout (see fig 6). EXO-200 is housed at the WIPP salt mine in New Mexico and is running since May 2011 with enriched xenon. An engineering run with an incomplete Pb shielding wall was made in December 2010 [2]. Soon after this Conference, EXO-200 has succeeded in measuring the $2\nu\beta\beta$ decay of ^{136}Xe with about one month of data [28] with a large S/N ratio, as shown in the energy spectrum of the measured decay reported in fig 7. This was the only unmeasured $2\nu\beta\beta$ decay rate among the double beta decay emitting isotopes being used for $0\nu\beta\beta$ decay searches (and the slowest directly measured with $T_{1/2} = 2.1 \cdot 10^{21}$ years). EXO-200 opens the way to 100-kg scale double beta decay experiments and has a projected half life sensitivity for $0\nu\beta\beta$ decay of $6{\cdot}10^{25}$ years with two years of running if a 1.5% (σ) energy resolution is reached (corresponding to 109-135 meV neutrino mass sensitivity).

[2] see R. Neilson's talk at this conference

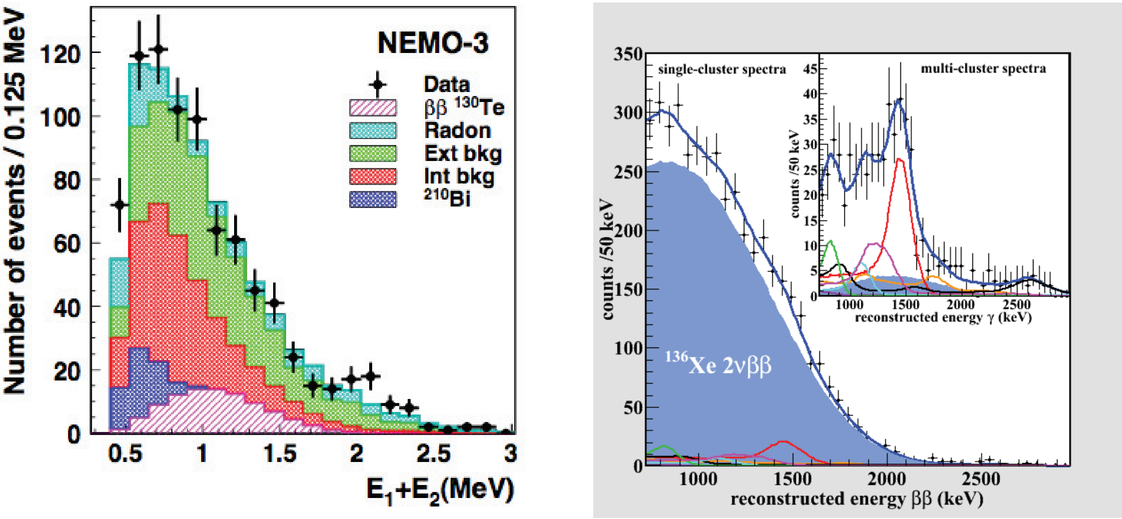

Fig. 7. Left: the $2\nu\beta\beta$ decay electron sum energy spectrum for ^{130}Te recently measured by NEMO3 ($T^{2\nu}_{1/2} = 7 \cdot 10^{20}$ years, from ref. [13]). The 2ν DBD half life of faster decaying isotopes was measured with even better S/N by NEMO3 [14]. Right: the electron sum energy spectrum of the $2\nu\beta\beta$ decay recently measured by EXO-200 ($T^{2\nu}_{1/2} = 2.1 \cdot 10^{21}$ years, from ref. [28]). The main panel shows the single ionization cluster events, while the inset depicts the multiple cluster events, dominated by multiple scattering γ ray interactions.

EXO is planning a large, tonne-scale experiment to follow EXO-200. The GXe and LXe options are currently being investigated. A defining feature of a large EXO experiment is a novel γ background suppressing strategy currently under R&D within the collaboration. The goal is to be able to identify the appearance of the ^{136}Ba daughter in coincidence with candidate $0\nu\beta\beta$ decays inside the detector. Barium tagging avenues being pursued include optical spectroscopy of singly charged ions in an atom trap or directly in the xenon medium [3]. A 10-tonne EXO with Ba tagging could reach a neutrino mass sensitivity better than 10 meV.

3. Conclusions and Acknowledgements

A summary of the experimental programs to search for neutrino-less double beta decay is given in table 2. The table reflects the selection made by the author for this review.

[3] see K. Twelker's talk at this conference

experiment	isotope	exposure [kg · years]	ν mass sensitivity [meV]	start date	reference
Majorana	^{76}Ge	50	150	2012-14	[29]
GERDA	^{76}Ge	15 (phase I)	270	2011	[30]
		100 (phase II)	110	2013 (?)	
CUORE	^{130}Te	22 (Cuore-0)	170-390	2012	[31]
		1000	41-95	2014	
SuperNEMO	^{82}Se	35	~50	2014	[32]
SNO+	^{150}Nd	44	100-200	2014	[33]
NEXT	^{136}Xe	200	~150	2013	[34]
KamLAND-Zen	^{136}Xe	800	~70	2011	[26]
EXO-200	^{136}Xe	280	~100	2011	[35]

Table 2. Summary of ongoing experimental programs to search for neutrino-less double beta decay.

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